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An Experimental Investigation of the Vortex-Sink Angular Rate Sensor.

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UNITED STATES
NAVAL POSTGRADUATE SCHOOL

THESIS

AN EXPERIMENTAL INVESTIGATION OF THE
VORTEX-SINK ANGULAR RATE SENSOR

by

Carlito Y. Cunanan

September 1968

[redacted]

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VORTEX-SINK ANGULAR RATE SENSOR

by

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Submitted in partial fulfillment of the
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September 1968

ABSTRACT

The purpose of this investigation was to experimentally determine the performance characteristics of certain probe geometries and their respective locations in the sink tube of a pneumatic angular rate sensor. Sensor response was determined for various flow rates and angular velocities for each test condition. It was found that the pickoff element placed inside the sink tube yields a longer linear-response range than the one placed outside the sink tube. Use of one of the special flow dividing plates, with the probe located outside the sink tube, improves the linear-response range of the sensor for all flow rates, but increases the magnitude of the response only for the lower flow rates. It was also observed that neither the shortening of the sink tube length downstream of the pickoff location nor the presence of a shallow circumferential groove at the midsection of the pickoff element alters the performance of the probe.

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LIST OF SYMBOLS

Q	total flow rate through the sensor, scfm.
p	pressure, psi.
p_o	ambient pressure, psi.
R_o	radius of pancake to the porous coupling, ft.
U_o	radial velocity at the pancake periphery, ft/sec.
U_s	average axial velocity in the sink tube, ft/sec.
V_{tpo}	tangential velocity at the pickoff holes, ft/sec.
ρ	fluid density, slugs/ft^3.
θ	angle from the horizontal axis of the sink tube.
$\Delta\theta$	$\tan^{-1} \frac{V_{tpo}}{U_s}$
ω	angular velocity of the sensor.

ACKNOWLEDGEMENTS

This investigation was carried out under the financial sponsorship of the Harry Diamond Laboratories of the United States Army Command, Washington, D. C. The author wishes to express his appreciation to Dr. T. Sarpkaya for his guidance and encouragement during the course of the investigation. He also wishes to thank Messrs. K. Mothersell, J. Beck and J. McKay who did numerous changes and modifications to the experimental equipment throughout the course of the investigation.

1. Introduction.

Surface vessels, submarines, airplanes and space vehicles depend upon control systems to prevent the occurrence of undesirable motions such as rolling, yawing, and pitching. Gyroscopes are presently used in these systems, but they have certain disadvantages such as sensitivity to shock, magnetic fields, vibrations, and friction. Electric components utilized for their operation are influenced by extremes in temperature and also by the presence of nuclear radiation.

In search of a simpler means of sensing the rotation of a body about a given axis, the behavior of a viscous fluid confined between two coaxial disks was considered [1]. This led to the study and development of the angular rate sensor.

A pneumatic angular rate sensor is a device which utilizes the changes in the characteristics of fluid flow to sense changes in the state of motion of the object to which the sensor is rigidly attached, and gives a mass and pressure output which is proportional to the rate at which the change of motion occurs. The output of the device may then be magnified and used to actuate other components of the system which will preserve with their reactions either the original or the desired state of motion.

The vortex-sink angular rate sensor consists basically of an ideal sink flow between two coaxial disks and a vortex created by the rotation of the sensor about its axis of symmetry, (Figure 1). Sink flow is defined as a type of potential flow in which the velocity at all points is directed radially towards the origin, where the fluid disappears [2].

Fluid is introduced at the periphery of the sensor through the porous coupling element, and in the absence of rotation, continues radially towards the sink. As the disks are rotated about their common axis, a

tangential velocity component is imparted to the fluid at the periphery. The fluid first flows in a two-dimensional spiral and changes to a three-dimensional swirl as it enters the sink tube.

The distribution of circulation in the sink tube initially consists of a forced vortex where the tangential velocity increases linearly with the radius, i.e., the core rotates as a single body so that each fluid particle has the same angular velocity, and a free vortex zone where the tangential velocity varies inversely with the radius in accordance with the free-vortex law which requires that the circulation remain constant [1], [3]. These two types of vortex motion merge at some point a as shown in Figure 2.

The strength of an ideal vortex is proportional to the rate of rotation. The determination of the rate of rotation, therefore, reduces to the determination of vortex strength either directly or indirectly through the measurement of certain dynamic characteristics of the fluid. The direct measurement of vortex strength is often difficult and requires the use of moving elements. On the other hand, the determination of mass and pressure output through the use of non-moving elements or pickoffs provides an indirect method for evaluating the strength of the vortex or the rate of rotation.

As the entire sensor assembly is rotated about the axis of the sink tube, the pressure differential created by the tangential component of velocity of the fluid is sensed by the pickoff. The pickoff element has two pressure pickoff holes oriented at 45 degrees to the flow in the sink tube. As the swirl approches the pickoff element, one hole feels the flow more radially and the other more tangentially, so that a pressure differential between the holes is established. The output of the pickoff element is fed into a differential pressure transducer and an electronic amplifier-recorder system.

This investigation is part of a continuing study, both theoretically and experimentally, on vortex rate sensors. The background material was described in the reference cited herein.

This investigation describes an experimental procedure in determining the performance characteristics of certain pickoff geometries and their respective locations in the sink tube.

The test conditions investigated involved the location and configuration of the pressure pickoff as follows;

1. Pressure pickoff inside the sink tube (Figure 3), i.e., 1-5/8" away from the inner pancake surface.
   a) Probe #2, (with long sink tube);
   b) Probe #2, (with short sink tube);
   c) Probe #2, (with a circumferential groove at the midsection and with a long sink tube);
   d) Probe #2, (with plate A glued at the groove in the midsection and oriented as shown in Figure 4, and with a long sink tube);
2. Pressure pickoff outside the long sink tube (Figure 3),
   a) Probe #2,
   b) Probe #2, (with plate B glued at the groove in the midsection as shown in Figure 4).

Probe #1 was a smooth pickoff element with the same geometric characteristics as Probe #2. It was used primarily to familiarize the writer with the operational characteristics of the sensor assembly and equipment. No experimental data was obtained with this probe.

2. Experimental Equipment and Procedure.

The experimental equipment consisted basically of a compressor, filter, inclined water manometer, porous coupling element, pancake assembly, pressure pickoff tube, microswitch-wiper device, pressure transducer, and an amplifier-recorder assembly. Figures 5 through 7 show the arrangement of the equipment.

Two large storage tanks of the air compressor were used to supply air at 140 $\pm$ 5 psig. Air was passed through a filter, three pressure regulators, and two valves located downstream and upstream of the pressure regulators, before being metered by the flowrator. A pressure gage (0-30 psig) was installed downstream of the flowrator to detect any variation in the back pressure so that the necessary correction factors could be applied to the flowrator readings.

The flowrator tube and float unit used gave a volume rate of 19.80 cfm of air at 14.7 psia, 70°F at 100% flow.

A slip ring mechanism made of plexiglass was used to supply air via four ½-inch tygon tubings from the stationary plenum chamber, located downstream of the flowrator, to the rotating rate sensor. The stationary part of the slip ring was fastened to the sensor frame. The rotating part was bolted to the outer wall of the pancake assembly. Six equally-spaced holes were drilled around the circumference and fitted with plastic tubings to supply air to the region between the porous coupling element and the outer seal of the sensor.

The porous coupling element was made of two 1/8 inch thick brass rings having 12-inch inside diameter and 15-inch outside diameter, as shown in Figure 1. Number 30 mesh brass strainer cloth was soldered around the outside and glued on the inside of the brass rings after a porous foam annulus was placed inside. The purpose of this wall was to assure a

uniform flow rate at the periphery of the pancake assembly by eliminating any cross-currents which might have been present.

The pickoff element, manufactured out of a stainless steel tube, had 0.041" OD and 0.026" ID. A dividing wall was placed in the tube at the midsection and two 0.013 inch diameter pressure pickoff holes were drilled on either side of an equidistant from the dividing wall, as shown in Figure 4. The pickoff holes were along one side of the wall and 0.040 inch apart. Collars and lockscrew mechanisms were fitted at both ends of the pickoff. One lockscrew unit also carried the lever-pointer used in the determination of the angular position of the pickoff element on a protractor fixed on the outside wall of the pancake assembly. Another lockscrew was utilized to position and secure the pickoff at the desired position along its longitudinal axis.

The pancake assembly was also made of plexiglass. The distance between the disks was .50". A sink hole 5/16" in diameter was drilled at the centerline of the coaxial disks, and the entrance rounded. The original design called for a removable sink tube body. A plastic extension to the sink tube was machined and fitted (Figure 3) so that the inside surface of the transition was smooth.

The experimental procedure consisted of determining the differential pressure output of the pickoff for rates of rotation from about 1 deg/sec. to 20 deg/sec. Two separate sets of runs were performed for each test condition. The tests were carried out for the flow rates of 5.94, 9.90, 13.86, and 17.82 scfm.

Prior to the experiments, the differential transducer was calibrated by using an inclined water manometer as the reference. Air pressure signal was fed into one side of the manometer so as to cause a one inch rise in the water level. When the water level was steady, the signal was switched

to one side of the differential transducer, which was connected to the recorder-amplifier assembly, and an appropriate gain was set.

The pressure pickoff holes in the probe were oriented for maximum response. This was done by first establishing a constant air flow and sensor rotation rate, and observing the pickoff output on the amplifier-recorder assembly. Small angular adjustments were made on the probe lever-pointer and the output noted on the recorder. It can be shown that positioning the holes 45 degrees from the direction of flow gives the maximum theoretical pressure differential across the two pressure pickoff holes (see Appendix A). When the maximum response was found, the pointer-lever was locked in position. The pickoff tube was then shifted along its longitudinal axis by inserting pieces of .003" and .001" stainless steel shims between the collar of the lever-pointer and the outside surface of the sink tube, and the output was observed on the recorder. When the position of maximum response was determined, the probe was secured in place by tightening the collar-lockscrew device on the other end of the pressure pickoff. The position of the pickoff holes along the long axis was found to be one of the most critical parameters in the experiment. This concluded the procedure for establishing the optimum angular and longitudinal position of the pickoff holes of the probe.

Two equal-length .34" ID polyethylene tubes were connected from the output sides of the probe to two corresponding input sides of the differential pressure transducer. The individual test runs were performed in the following manner;

a) While the sensor was stationary, the desired flow rate was set at the flowrator and allowed to flow for some time to stabilize the system.

b) The microswitch-wiper unit was connected to the remote event marker of the amplifier. This device helped to determine the rate of rotation of the sensor by counting the number of seconds it takes to rotate 60 degrees.

c) Attenuation on the amplifier was set and the stylus zeroed at the convenient reference line.

d) The sensor was set in motion at various rotation rates and the magnitude of the pressure differential output was recorded with the amplifier-recorder assembly. Twenty to thirty seconds were allowed between various rates of rotation to stabilize the system at a new condition.

e) The sensor was stopped and an increased flow rate was set at the flowrator. Steps c) and d) were repeated until all of the four flow rates previously mentioned were covered.

f) The pickoff tube was removed and changes were made on it either by introducing modifications on its geometry or by merely changing the probe position in the sink tube.

g) Calibration of the amplifier-recorder assembly was checked and re-calibration procedures were performed when necessary.

h) The probe was re-positioned in the sink tube. Steps were carried out to make sure that the orientation of the probe was one which gave the maximum response.

i) Steps a), b), c), d), and e) were repeated for this particular probe geometry/position.

j) Steps f), g), and h) were repeated.

A sample recording of the pressure differential is shown in Figure 8. The experimental data obtained in the tests were reduced and plotted in terms of the pressure differential output versus the angular velocity of the rate sensor.

Experimental Uncertainty.

This investigation was a single-sample data experiment. The three quantities determined were the pressure differential Δp expressed in psi and the sensor angular velocity ω expressed in deg/sec., and the flow rate Q expressed in scfm. Experimental errors were primarily observational inaccuracies and are listed below with the respective value which yielded the maximum uncertainty, namely;

CR = 4 $\pm$ .05 (Δ p recording on the chart paper)

CC = 1 $\pm$ .01 (inclined water manometer reading)

CS = 4 $\pm$ .05 (chart speed reading)

CD = 30 $\pm$ .04 (micro-switch wiper 60 -deg spacings)

Q = 30 $\pm$ .02 (flowrator reading)

Using the method of Kline and McClintock [5] and the notation $\bar{\omega}_X$ as the uncertainty in X, the experimental uncertainty interval expression for Δp, ω and Q are;

$$\bar{\omega}_{\Delta p} = \left[\left(\frac{\partial \Delta p}{\partial CR} \bar{\omega}_{CR} \right)^2 + \left(\frac{\partial \Delta p}{\partial CC} \bar{\omega}_{CC} \right)^2 \right]^{1/2}$$

$$\bar{\omega}_{\omega} = \left[\left(\frac{\partial \omega}{\partial CS} \bar{\omega}_{CS} \right)^2 + \left(\frac{\partial \omega}{\partial CD} \bar{\omega}_{CD} \right)^2 \right]^{1/2}$$

$$\bar{\omega}_{Q} = \left[\left(\frac{\partial Q}{\partial Q} \bar{\omega}_{Q} \right)^2 \right]^{1/2}$$

Simplifying and substituting the appropriate values, the above equations yield

$$\frac{\bar{\omega}_{\Delta p}}{\Delta p} = \pm .051$$

$$\frac{\bar{\omega}_{\omega}}{\omega} = \pm .064$$

$$\frac{\bar{\omega}_{Q}}{Q} = \pm .02$$

which are well within the acceptable limits of experimental uncertainty.

3. Discussion of Results and Conclusions.

The differential pressure versus the rate of rotation is shown in Figures 9 through 13 for each test condition investigated. The slope of the linear portion of the curves is defined as the response of the sensor and is expressed in psi/deg/sec. The response was linear at small angular velocities and became non-linear at higher rates of rotation. This non-linearity at higher angular velocities is not a major disadvantage as the sensor is intended to operate at small rates of rotation.

A careful examination of these graphs revealed that the best pickoff location for maximum response was the one inside the sink tube. This position resulted in responses of .01 psi/deg/sec and .0025 psi/deg/sec for the flow rates of 17.82 scfm and 5.94 scfm respectively. The linear response ranges for these two flow rates were 15.0 deg/sec and 10.8 deg/sec respectively.

The same pickoff element placed outside the sink tube gave shorter linear response ranges for the same flow rates. At the lowest flow rate observed, the response was nonlinear for the incremental values of the rates of rotation examined. It can be safely assumed that the range of linearity was below the lowest observed value of the angular rotation. At the higher flow rates, the sensor response compared favorably in magnitude with those obtained from the pickoff element placed inside the sink tube.

Sarpkaya [6] has shown that the differential pressure sensed at the pickoff location is proportional to the angle, Θ, that the velocity vector makes with the axis of the sink tube, and that $\Delta\Theta = \frac{V_{tpo}}{U_s}$
For maximum response, the pickoff element must be located some distance downstream of the vena contracta [4] but before the forced vortex has

gained enough size to decrease the tangential velocity at the pickoff holes. Figure 2 shows a qualitative illustration of the tangential velocity distribution in the sink tube.

At lower flow rates, the angle that this velocity vector makes with the radial direction is larger so that the fluid element travels a longer spiral path before reaching the pickoff holes. This means that the amount of circulation retained at the pickoff is reduced because the viscous shear forces have a greater area over which to remove energy from the fluid particle.

Placing the pickoff element outside the sink tube, i.e., further downstream of the vena contracta, reduced the response of the pickoff, particularly for lower flow rates.

In order to determine the effects of slight changes in the geometry of the sink tube, the plastic sink tube extension was removed. Shortening the sink tube axial dimension downstream of the pickoff location inside the sink tube did not alter the response characteristics of the pickoff element. The presence of a circumferential groove at the midsection of the pickoff element, likewise, did not affect the performance of the pickoff.

The use of plate A (Figure 4) with the probe gave a sensor response of .0028 psi/deg/sec for the highest flow rate and .00067 psi/deg/sec for the lowest flow rate observed. This is 25% - 30% less than the sensor response attained for the smooth pickoff element in the same location. The linear range for the highest flow rate is only about 8.6 deg/sec.

The use of plate B (Figure 4) in the probe located at the end of the sink tube gave a sensor response of .0095 and .0025 psi/deg/sec corresponding to the highest and lowest flow rates observed. The linear range

increased for all flow rates when compared with those obtained using the smooth tube in the same location, but did not get quite as high as those obtained with the smooth tube placed inside the sink tube. To verify and evaluate further the effects of plate B on the probe, the normalized pressure coefficient $\frac{\Delta P}{\rho/2\, U_0^2} \times 10^{-3}$ and the non-dimensional parameter $\frac{\omega R_0}{U_0}$ were plotted as shown in Figures 14 and 15. It is clear from the latter graph that the use of plate B does indeed improve the linear response range of the pickoff element.

It is obvious that the flow in the sink tube and about the pickoff exhibit highly complex nonlinear characteristics due to a number of properties which include the compressibility of the fluid, the turbulent and non-uniform structure of the flow, and the complexity of the device geometry. Primarily for these reasons, it seems impossible to attain a complete theoretical understanding which will provide a framework for interpreting the body of extensive experimental knowledge.

In summary, therefore, the following conclusions may be reached:

1) The placing of the pickoff element inside the sink tube gives a longer linear response range than that of the one placed outside the sink tube.

2) The use of plate A in the probe located inside the sink tube decreased not only the magnitude but also the linear range of the sensor response. Furthermore, at lower flow rates, there was a reversal in the algebraic sign of the differential pressure for angular rates larger than 11.0 deg/sec. It is obvious that this plate geometry should not be used.

3) Shortening the sink tube length downstream of the pickoff location does not affect the probe performance characteristics and neither does the presence of a shallow circumferential groove at the midsection of the pickoff element.

4) The use of plate B, with the probe located at the end of the tube, improved the linear response range of the pickoff for all flow rates observed, but increased the response magnitude only for the lower flow rates.

4. Recommendations for Future Work.

1) Carry out a theoretical analysis to determine the radius of curvature of that portion of the pancake disks that bounds the entrance to the sink tube. This may be done either through the use of the axisymmetric potential flow theory by freezing one of the streamlines or through the numerical solution of the Navier-Stokes equations for axisymmetric swirling flows.

2) Use smaller diameter pickoff elements.

3) Use other flow-dividing plate geometries.

4) Obtain a theoretical solution to vortex motion in the sink tube in the vicinity of the pickoff element with a plate at the mid-section.

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APPENDIX A

Pickoff Holes Orientation for Optimal Response.

The pressure distribution around a cylinder located in a uniform fluid flow U_s is given by

1) $$P = P_0 + \frac{\rho}{2} U_s^2 \left(1 - 4 \sin^2 \theta\right) .$$

Differentiating with respect to θ, we get

2) $$\frac{\partial P}{\partial \theta} = - 8 \frac{\rho}{2} U_s^2 \sin \theta \cos \theta .$$

To find the maximum of $\frac{\partial P}{\partial \theta}$, we differentiate equation 2) and get

$$\frac{\partial^2 P}{\partial \theta^2} = - 8 \frac{\rho}{2} U_s^2 \cos 2 \theta$$

and equating this equation to zero yields $\theta = \pm \pi/4$.

For largest response, therefore, the pickoff holes must be oriented such that $\theta = \pm \pi/4$.

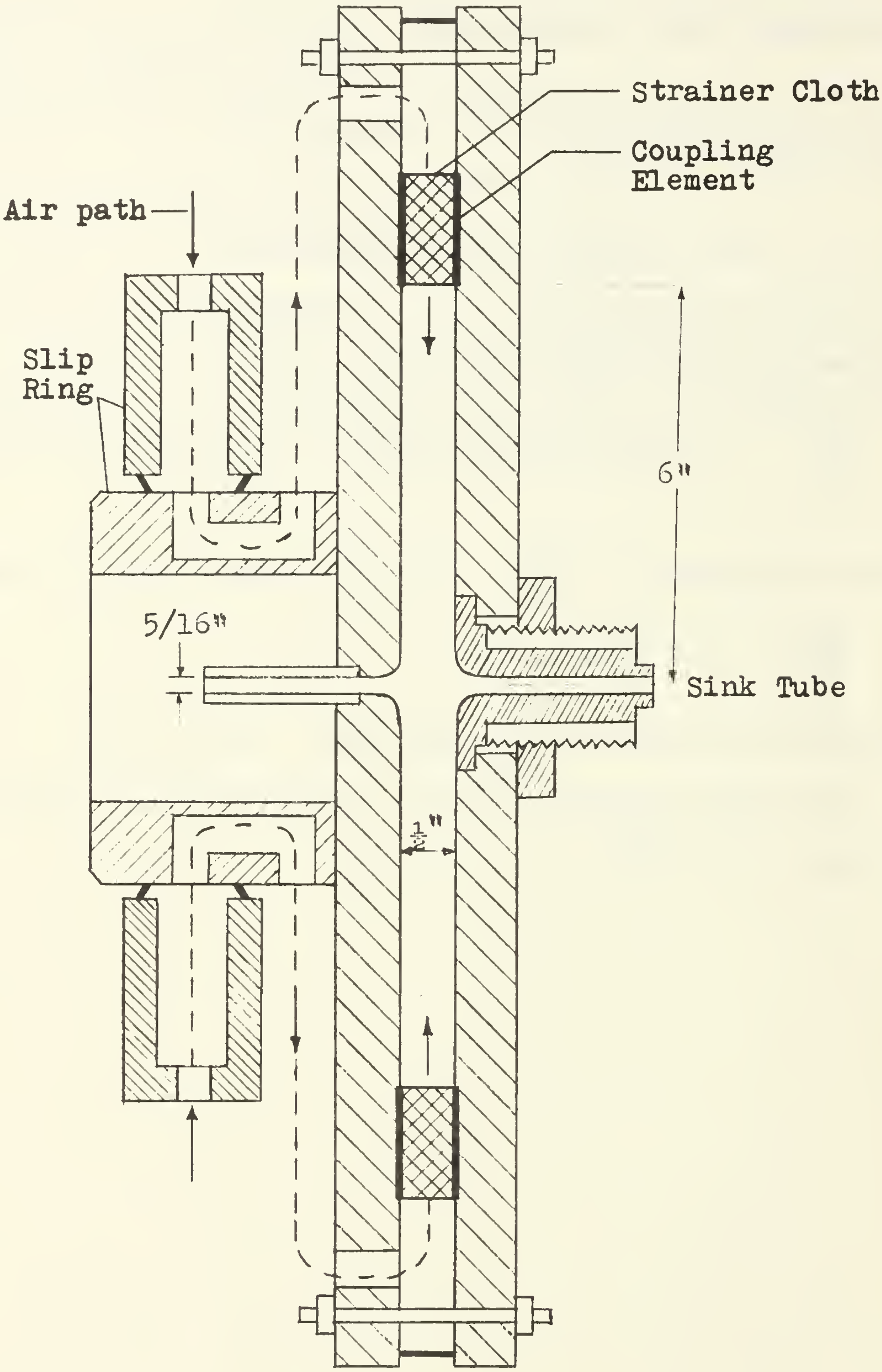


FIG. 1 SENSOR ASSEMBLY

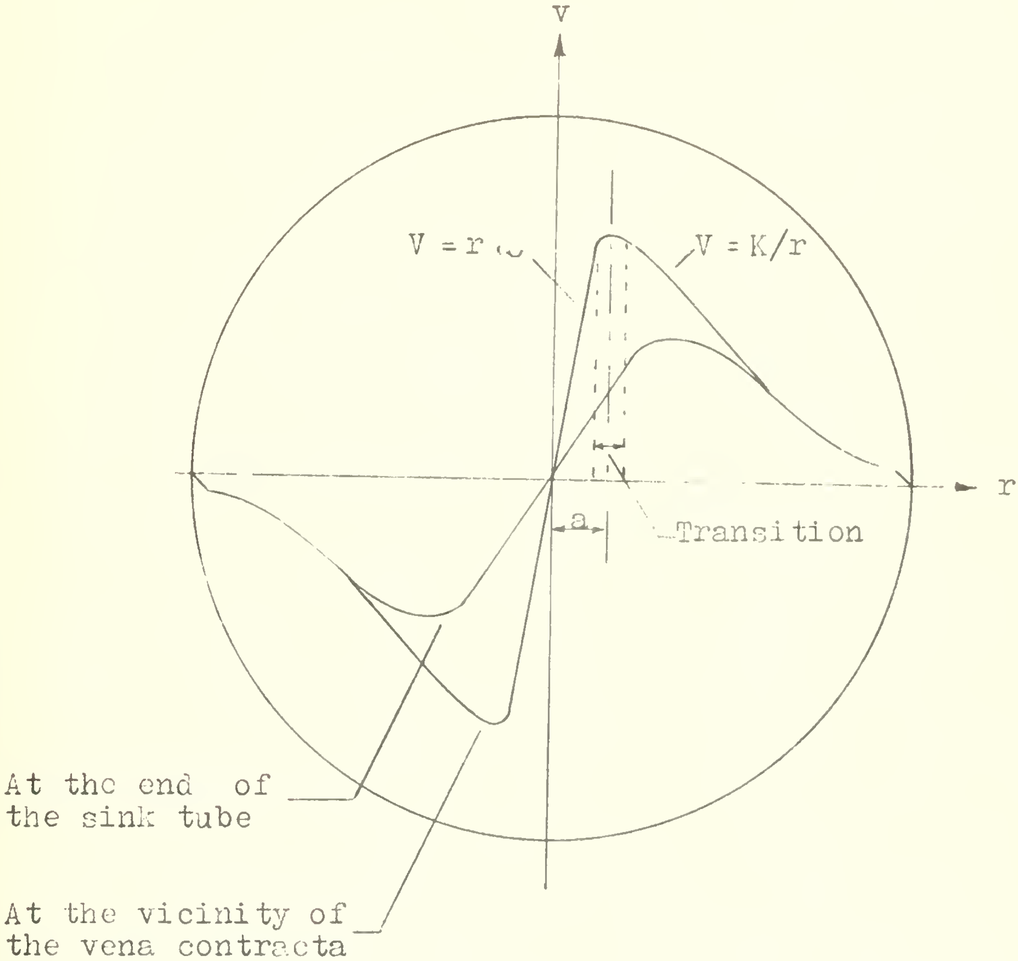
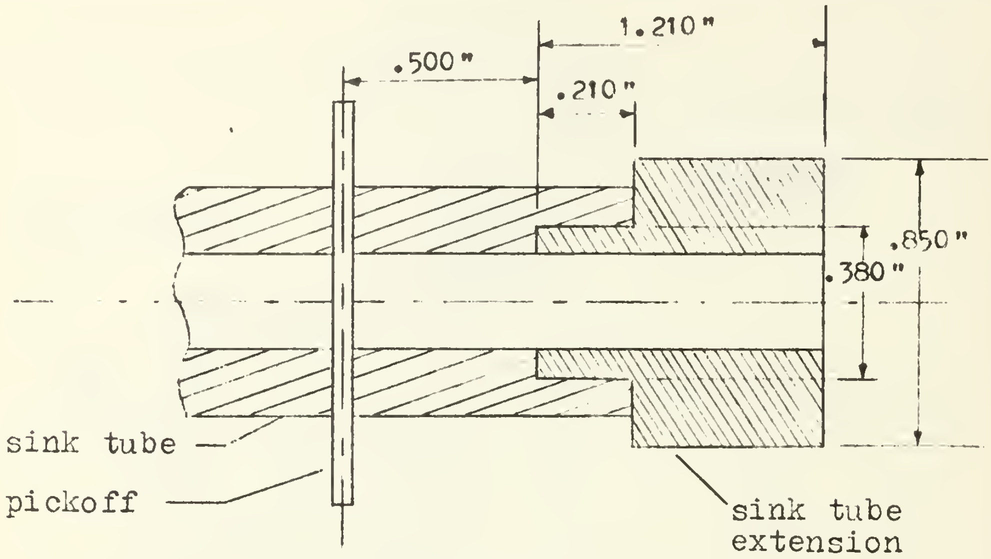
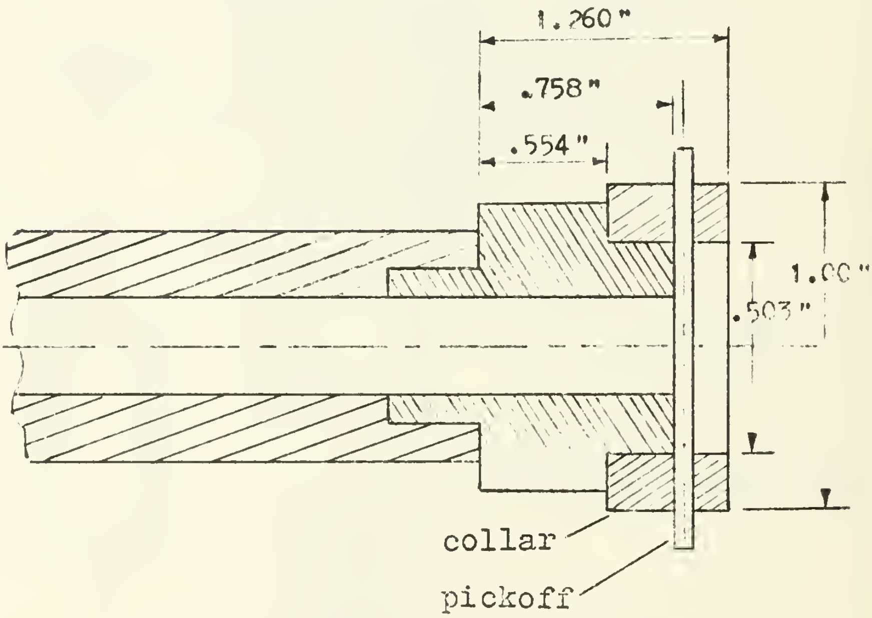


Fig. 2 Tangential Velocity distribution in the Sink Tube



Pickoff Inside of Sink Tube



Pickoff Outside of Sink Tube

Fig. 3 Pressure Pickoff Location

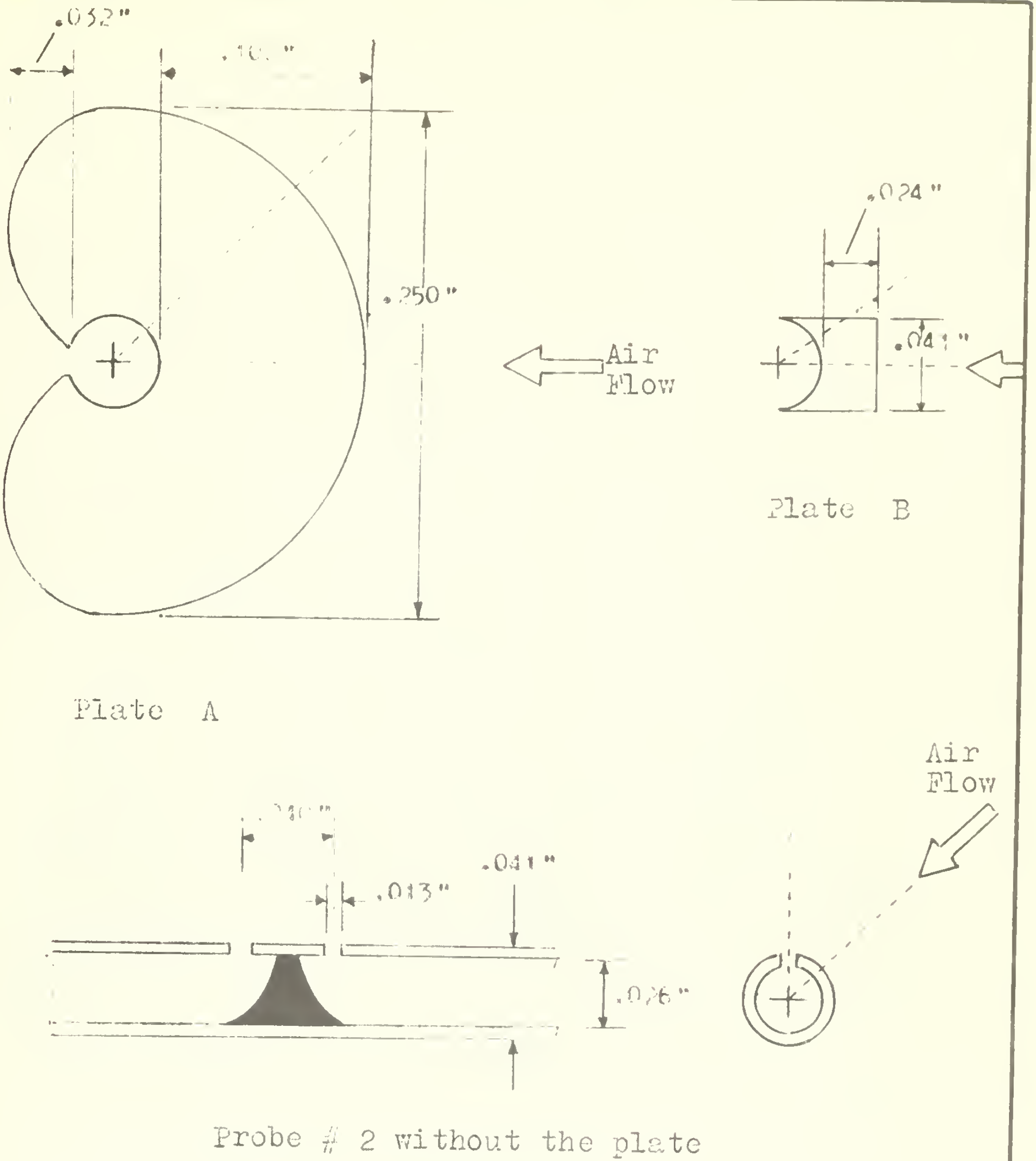


Fig. 4 Pickoff Geometry

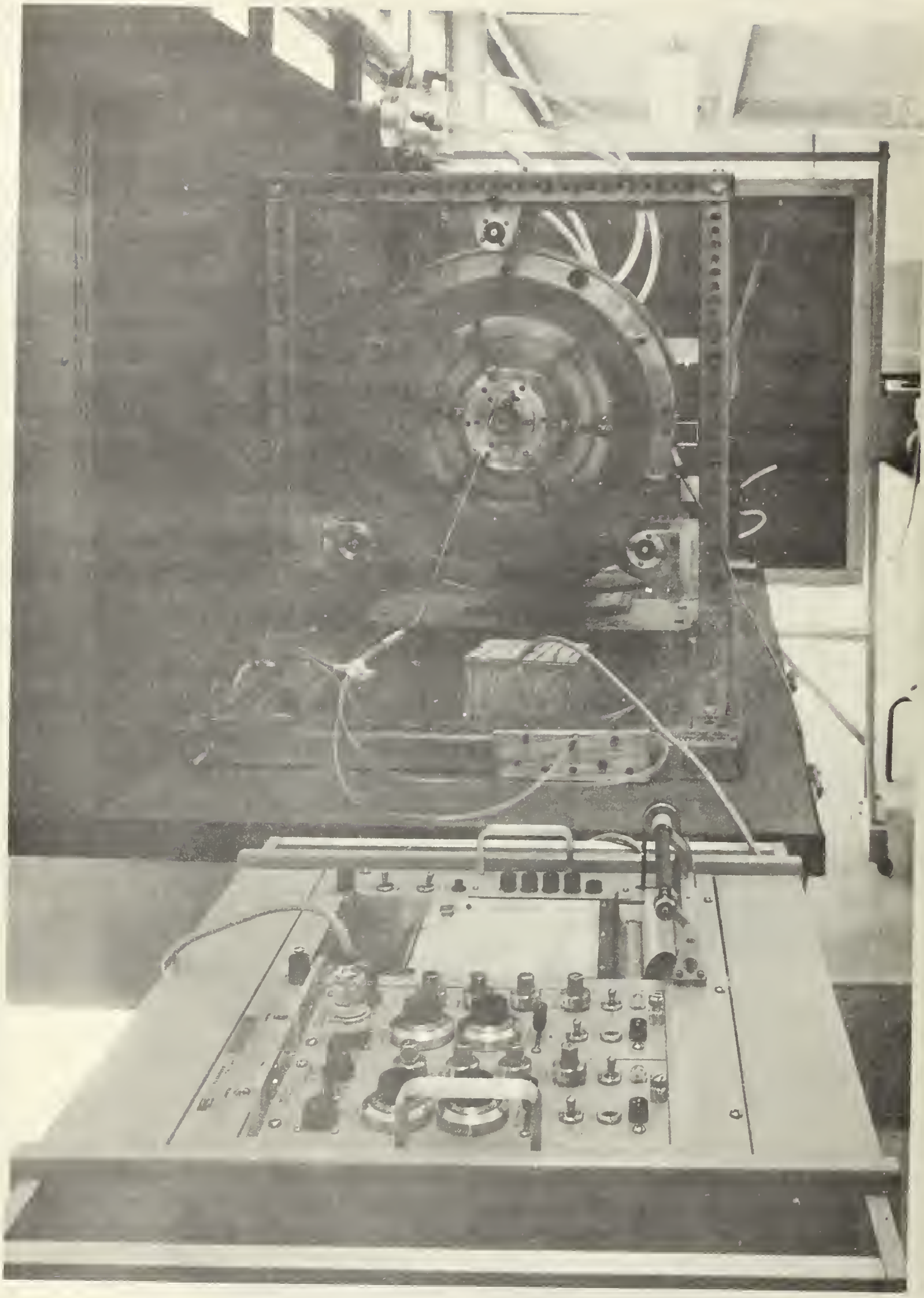


Fig. 5 Arrangement of Experimental Apparatus

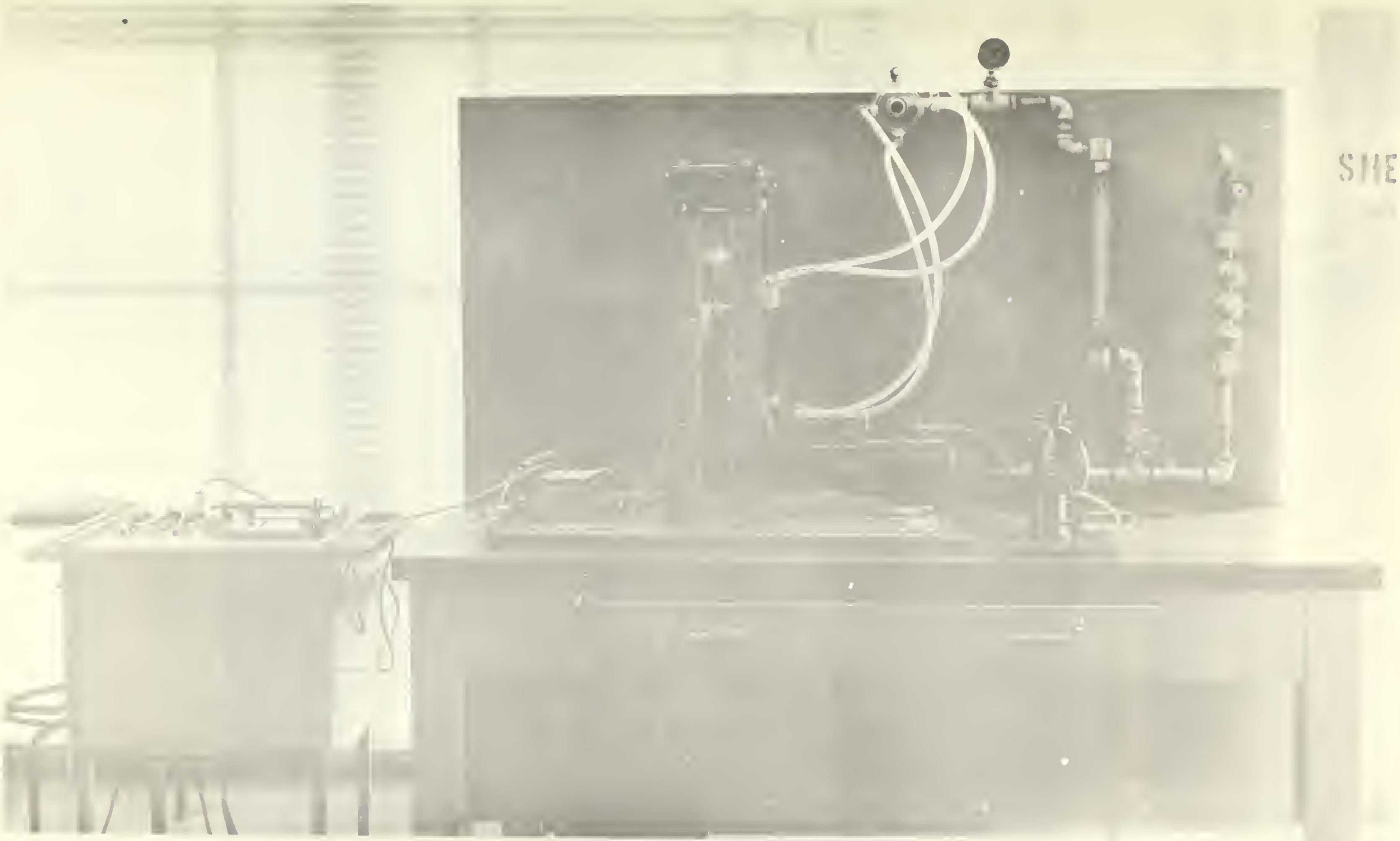


Fig. 6 Arrangement of Experimental Apparatus

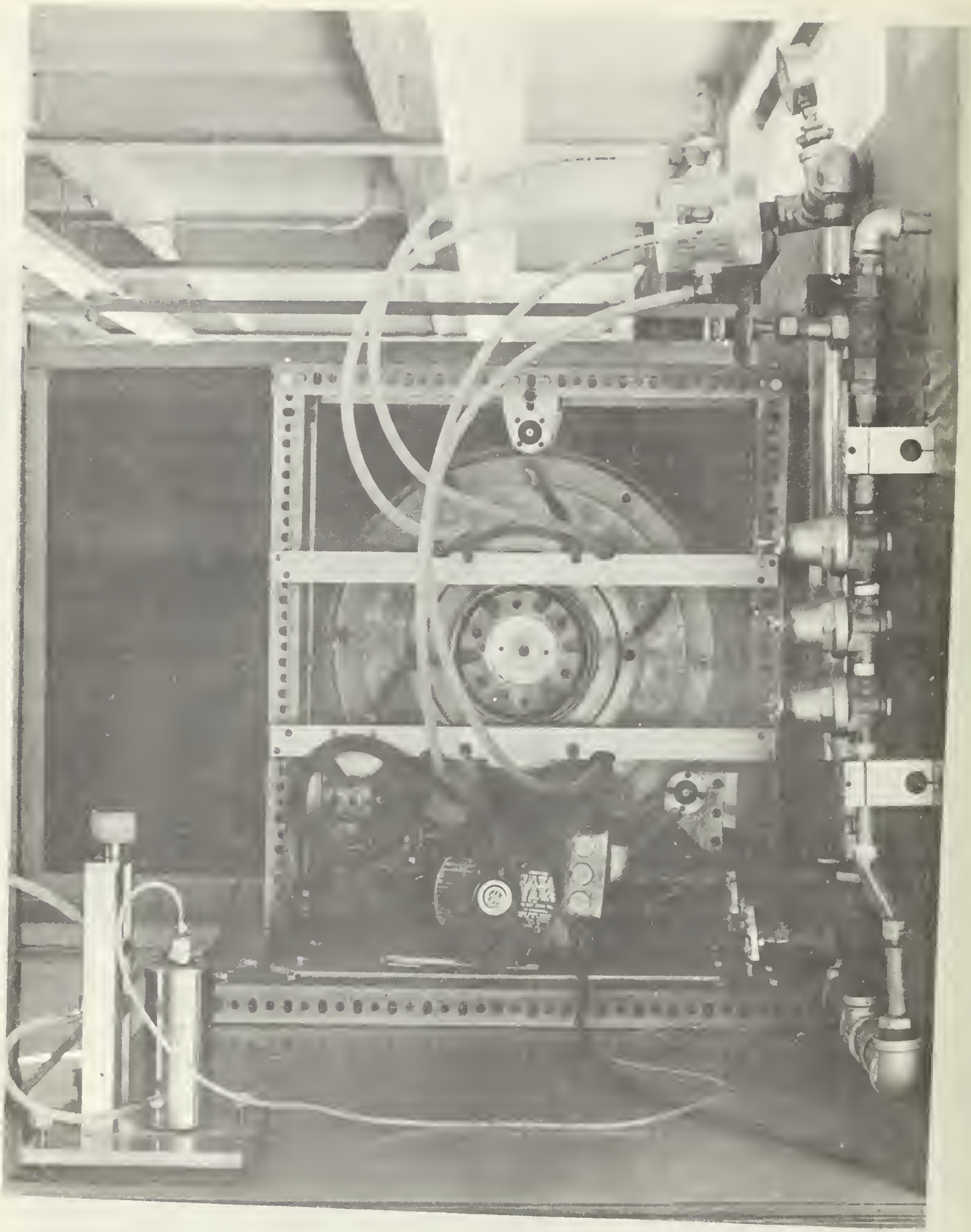


Fig. 7 Arrangement of Experimental Apparatus

Portion of Run # 2

6 August 1968

Probe # 2

Inside the long sink tube

Flow rate = 50%

Amplifier-recorder settings:
Attenuation : X10
Gain scale : 50 mm = 1" H_2O at X1
Chart speed : 5 mm/sec.

Event marker : triggered every 60 deg

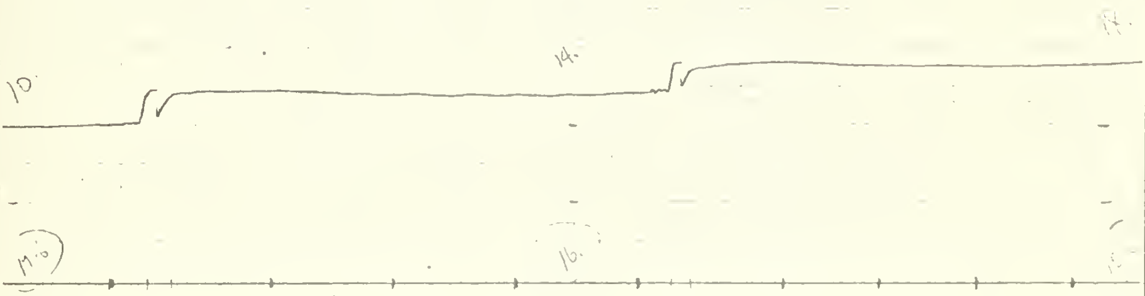


Fig. 8 Sample Recording of Differential Pressure

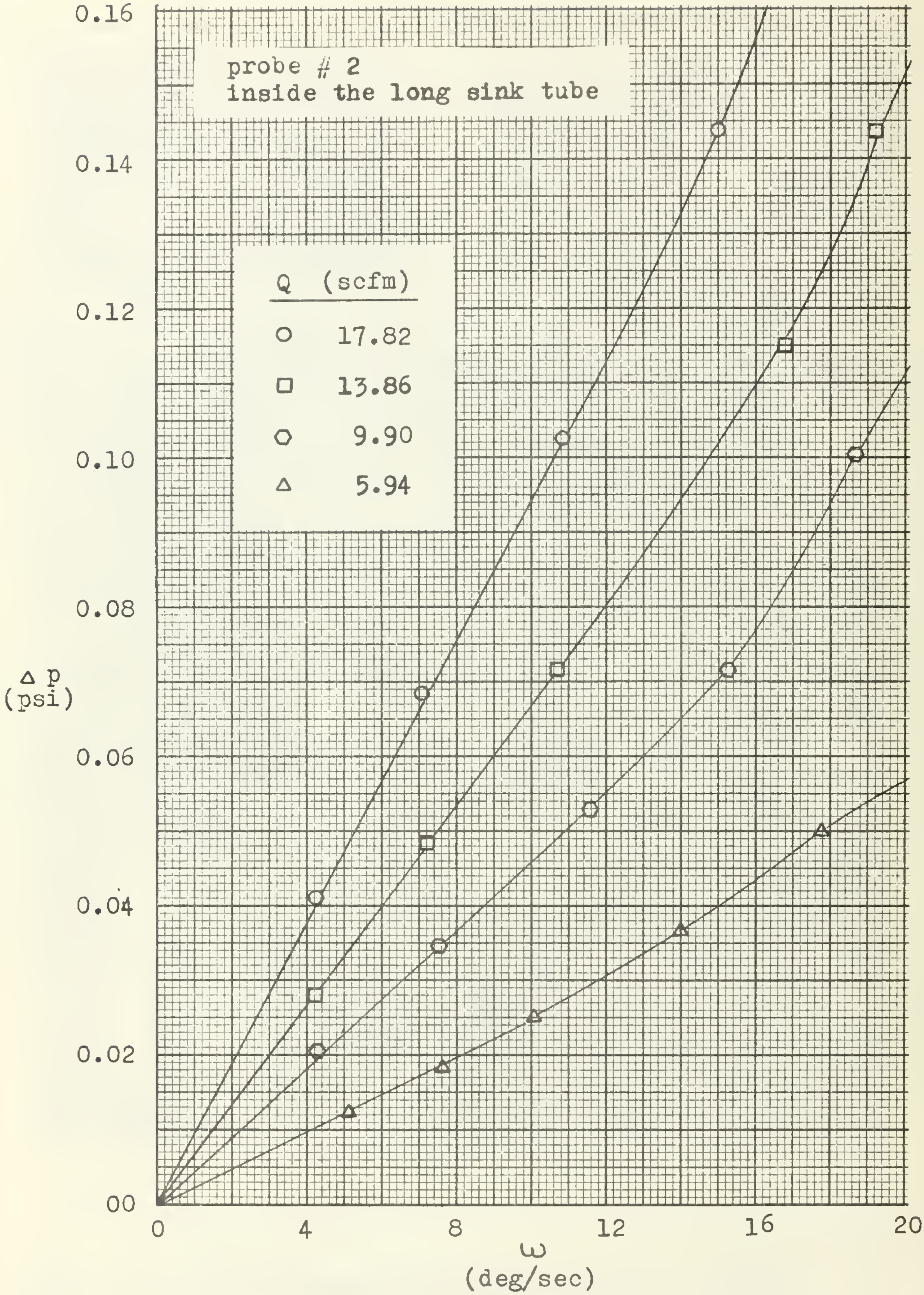


Fig. 9 Differential Pressure versus Angular Velocity

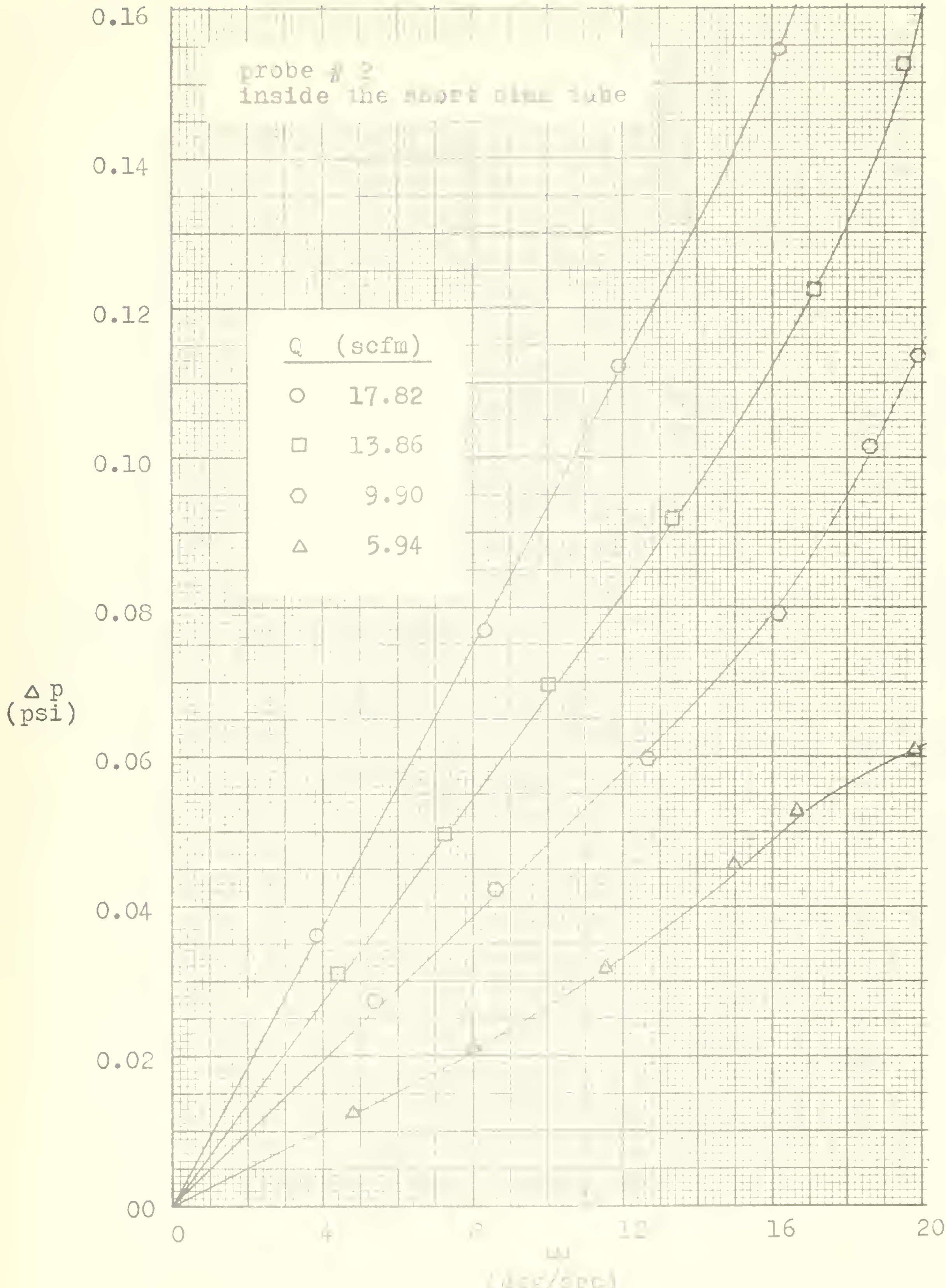


Fig. 10 Differential Pressure versus Angular Velocity

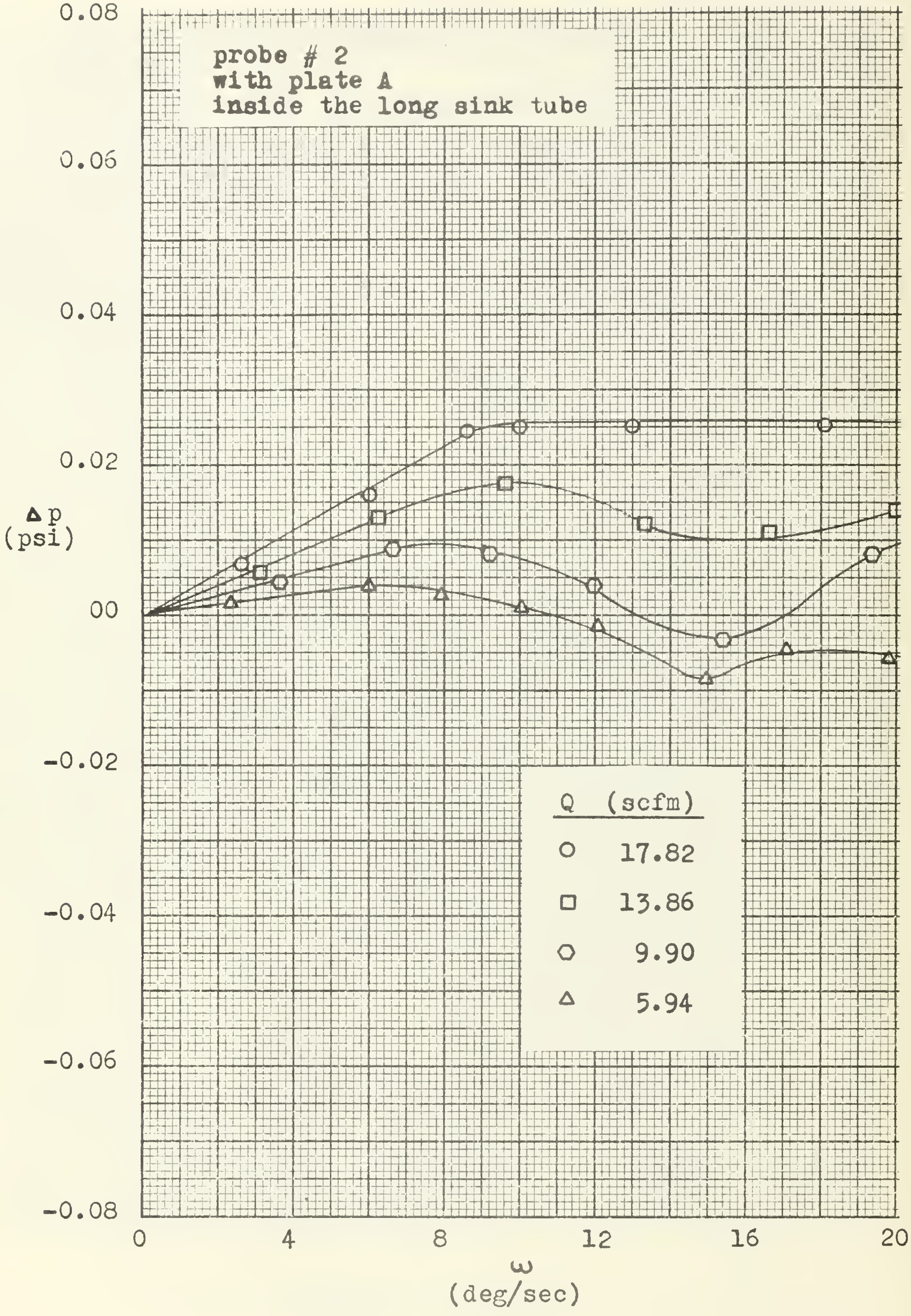


Fig. 11 Differential Pressure versus Angular Velocity

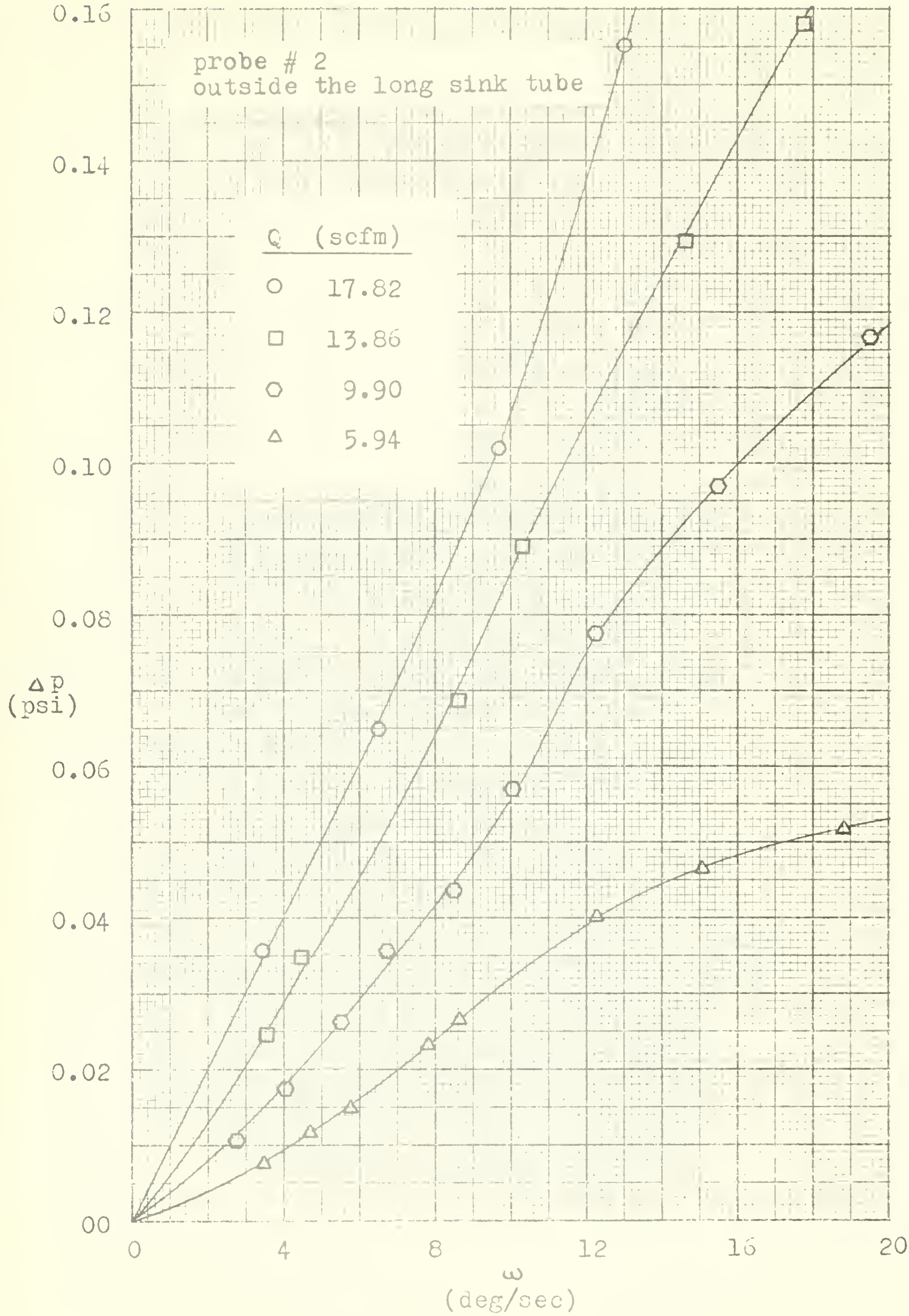


Fig. 12 Differential Pressure versus Angular Velocity

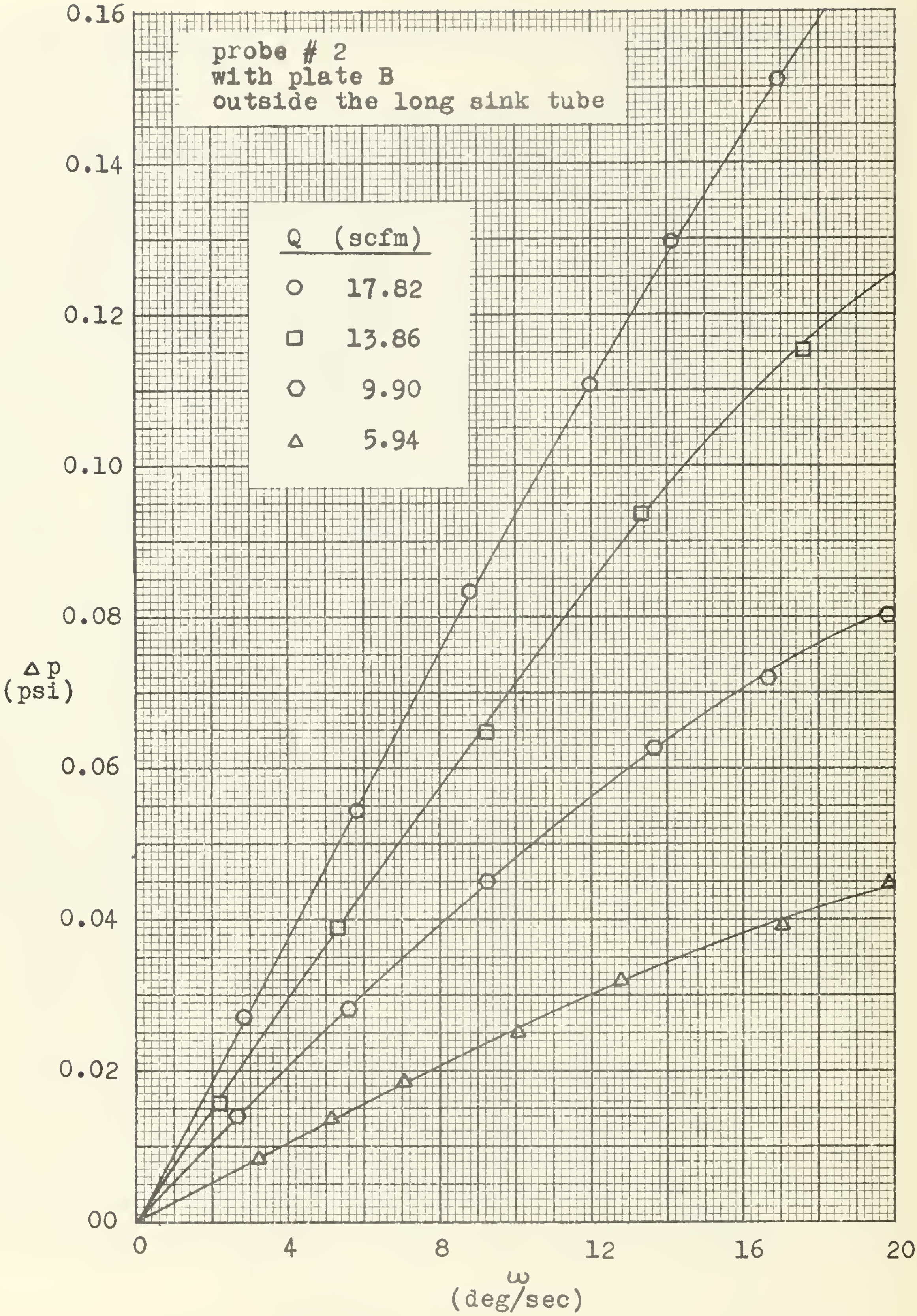
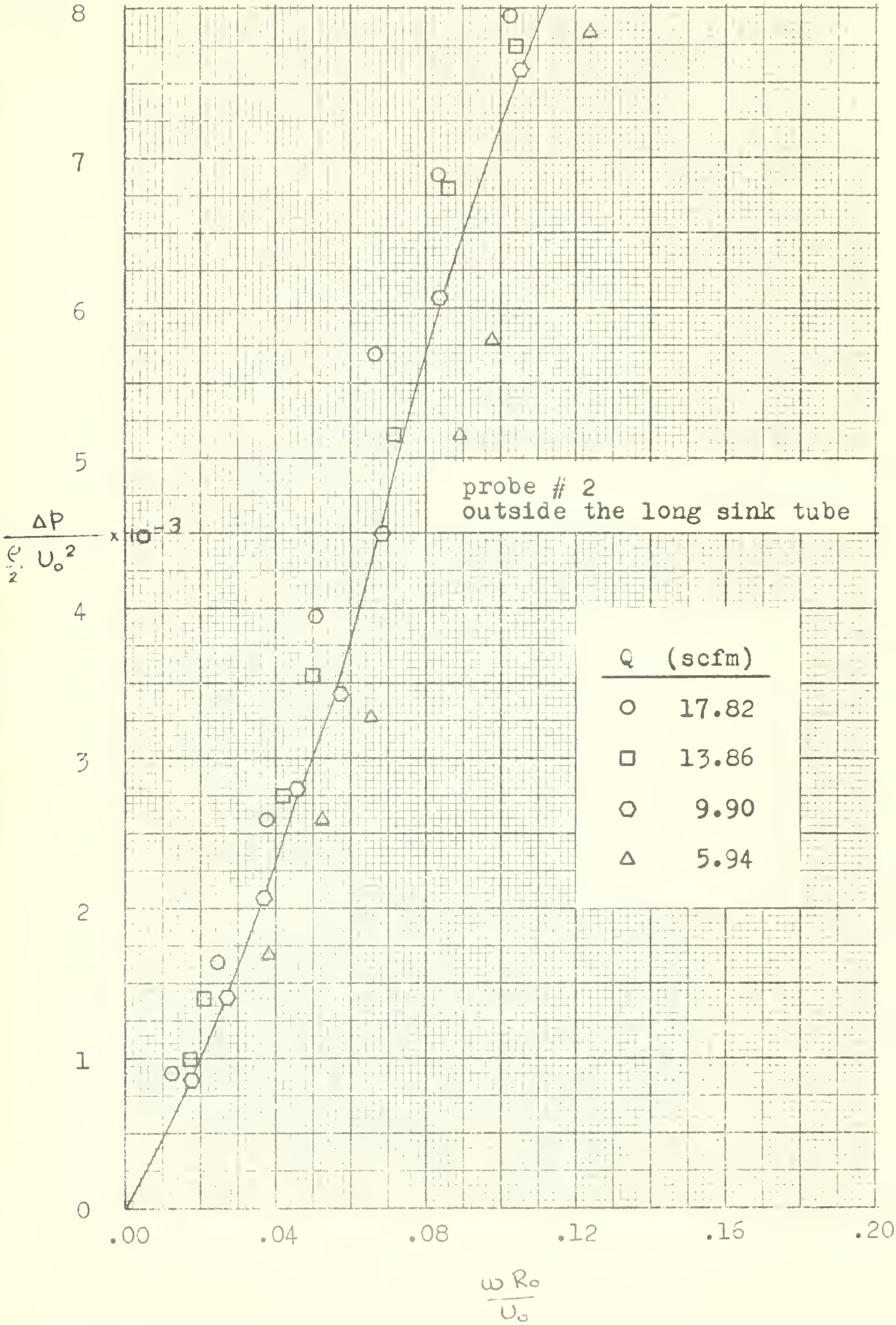
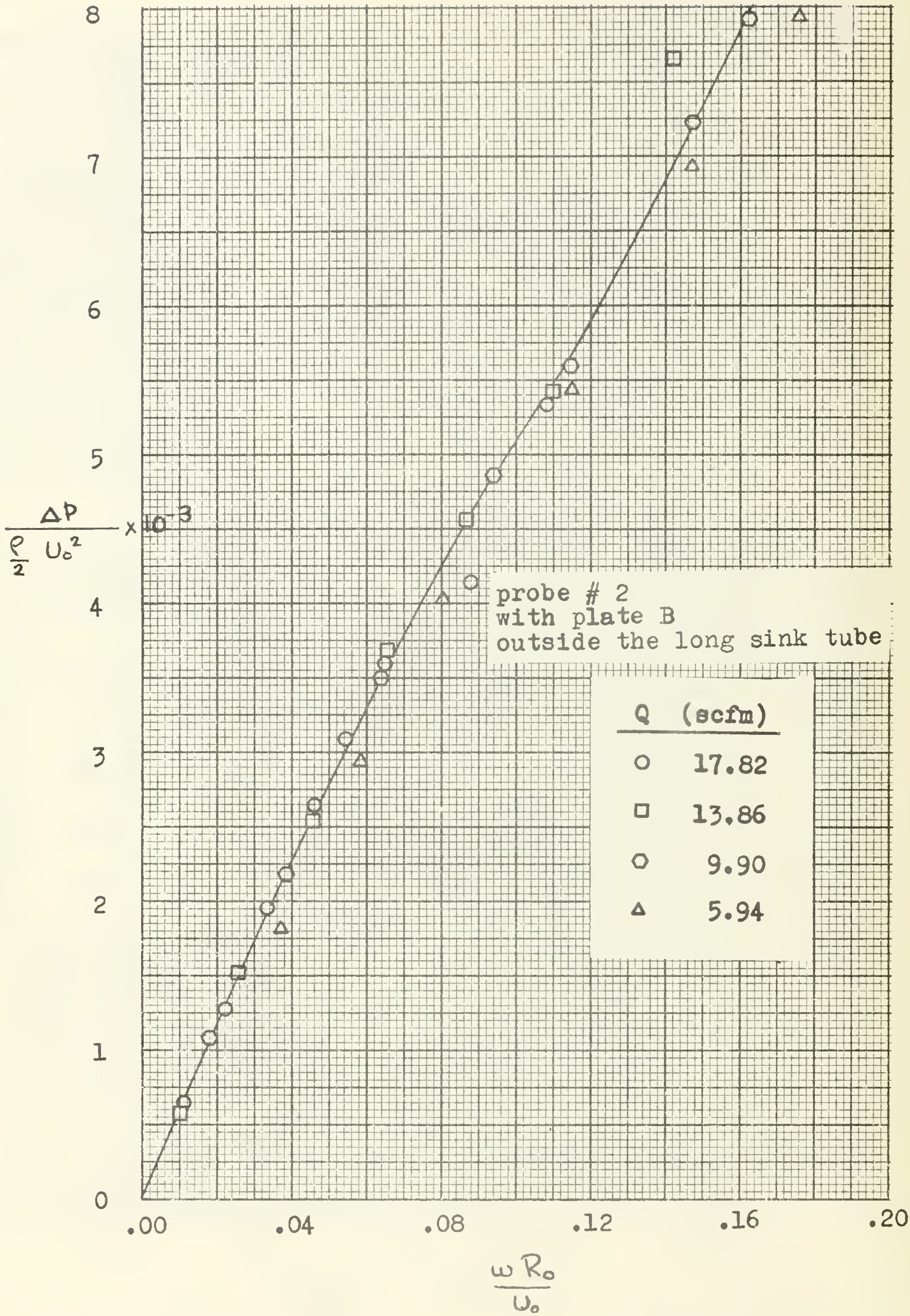


Fig. 13 Differential Pressure versus Angular Velocity



8
7
6
5
4
3
2
1
0
$\frac{\Delta P}{\frac{\rho}{2} U_o^2} \times 10^{-3}$
probe # 2
outside the long sink tube
Q (scfm)
17.82
13.86
9.90
5.94
.00
.04
.08
.12
.16
.20
$\frac{\omega R_o}{U_o}$

Figure 14



8
7
6
5
4
3
2
1
0
$\frac{\Delta P}{\frac{\rho}{2} U_o^2} \times 10^{-3}$
.00
.04
.08
.12
.16
.20
$\frac{\omega R_o}{U_o}$
probe # 2
with plate B
outside the long sink tube
Q (scfm)
17.82
13.86
9.90
5.94

Figure 15

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13. ABSTRACT

The purpose of this investigation was to experimentally determine the performanc characteristics of certain probe geometries and their respective locations in the sink tube of a pneumatic angular rate sensor. Sensor response was determined for various flow rates and angular velocities for each test condition. It was found that the pickoff element placed inside the sink tube yields a longer linear-response range than the one placed outside the sink tube. Use of one of the special flow dividing plates, with the probe located outside the sink tube, improves the linear-response range of the sensor for all flow rates, but increases the magnitude of the response only for the lower flow rates. It was also observed that neither the shortening of the sink tube length downstream of the pickoff location nor the presence of a shallow circumferential groove at the midsection of the pickoff element alters the performance of the probe.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Distribution of circulation in the sink tube						
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Senor response						